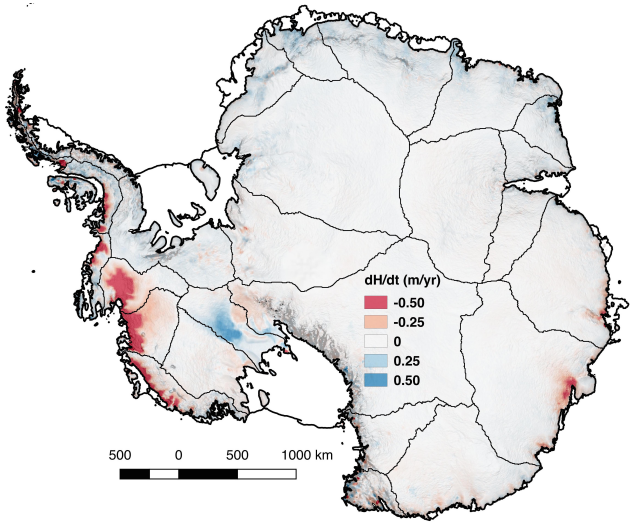
Integration of nearly 30 years of disparate satellite altimetry observations of the Antarctic ice sheet, 1985-2018



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AGU Meeting 2018, Washington D.C, U.S.A

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Introduction

- Satellite and airborne altimetry provide the longest continuous record from which the mass balance of the Antarctic ice sheet can be derived, starting with the launch of ERS-1 in 1991.
- Accurate knowledge of the long-term mass balance is vital for understanding the geophysical processes governing the ice sheet contribution to present day sea-level rise.
- However, this record is comprised of several different measurement systems: with different orbit parameters, effective topography (sampling, penetration, etc..), measurement configuration (pulse-limited, interferometric, laser etc.).
- This poses a major challenge on the interpretation and reconstruction of consistent elevation-change time series for determining long-term ice sheet trends and variability.

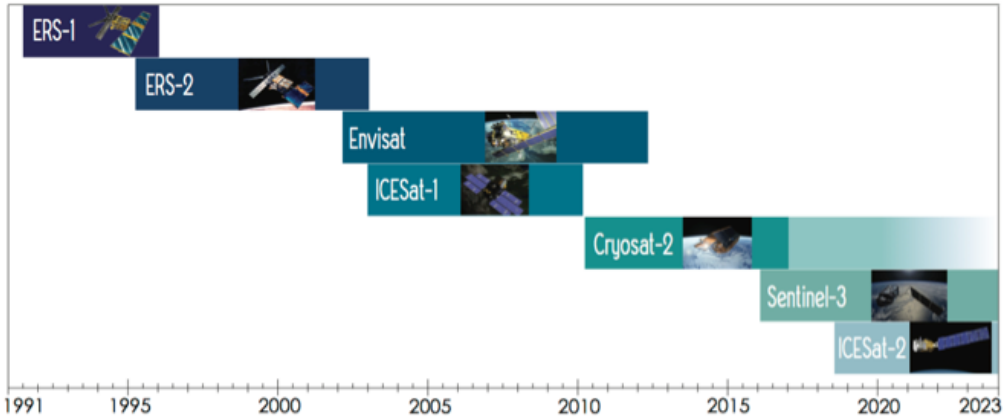
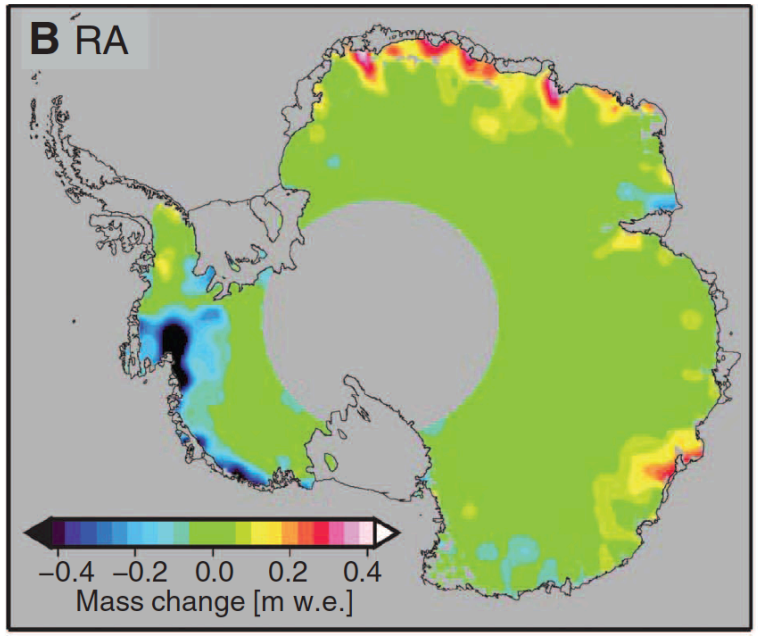


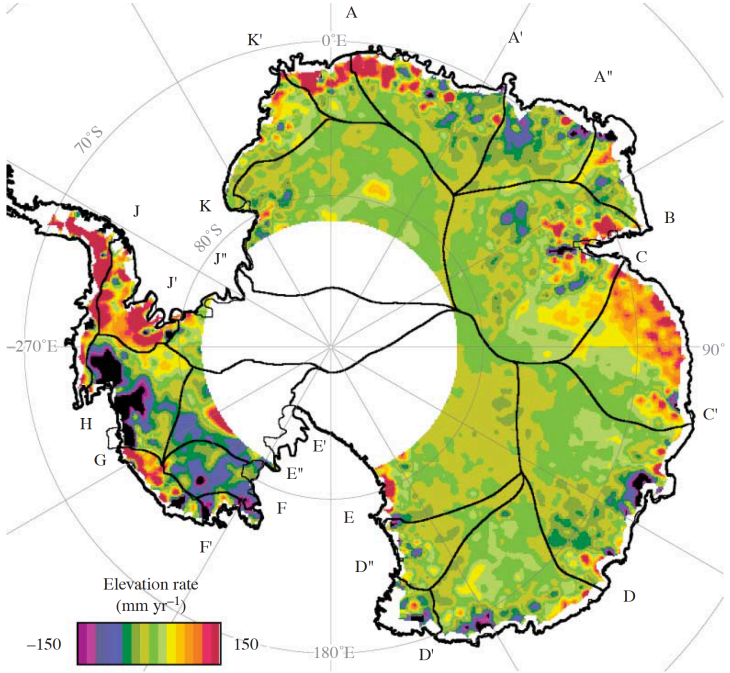
Figure 1. Past, present and future altimetry record

Elevation Change of the Antarctic Ice Sheet

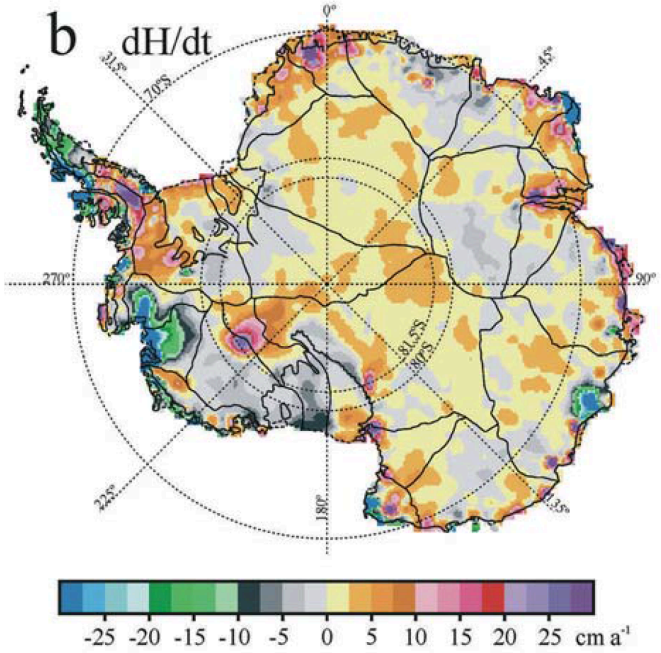
Multi-mission elevation change rates:



Shepherd et al. 2012



Wingham et al. 2006



Zwally et al. 2005

Methodology and Data

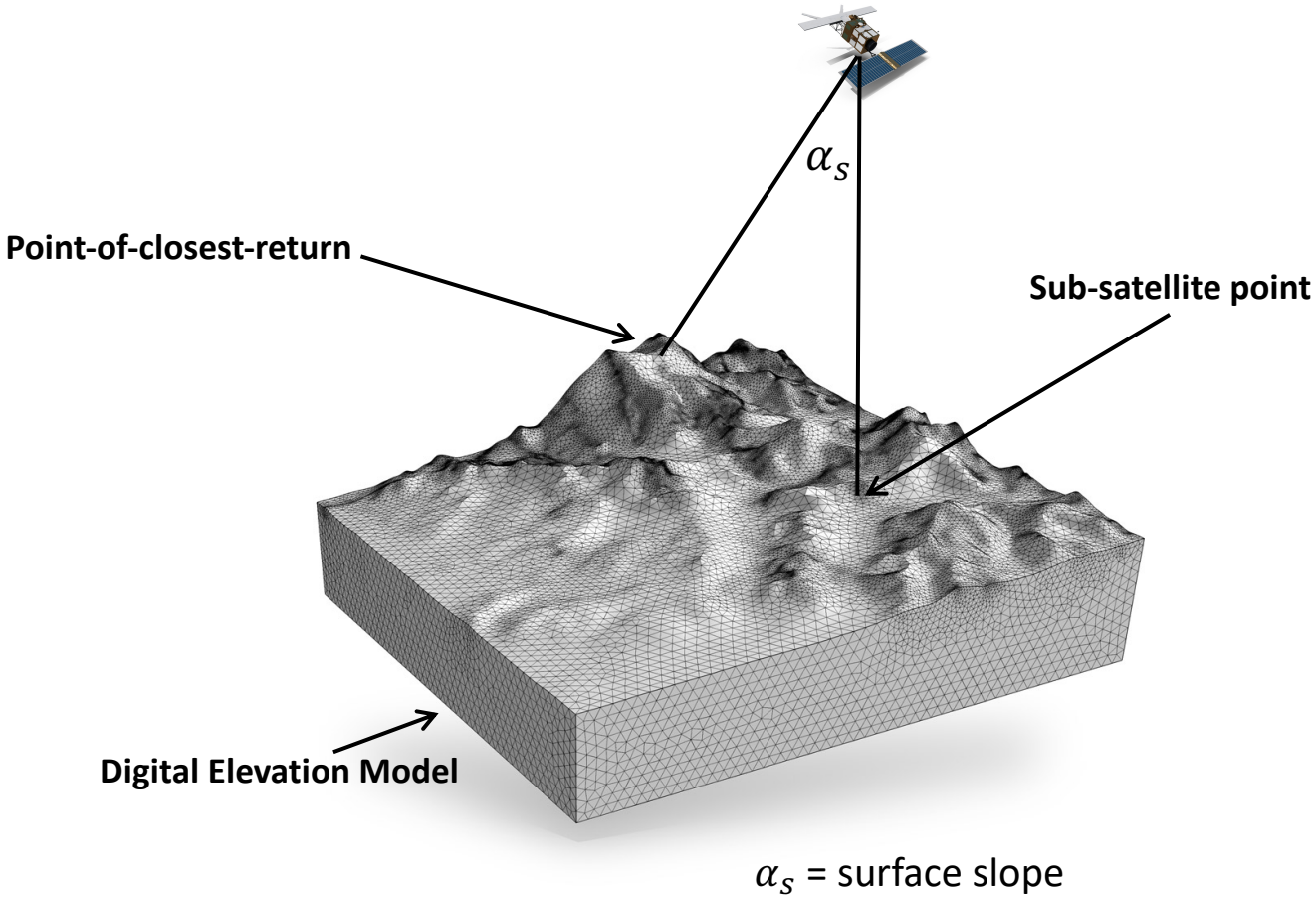
Processing Methodology:

- Slope Correction
- Topography Removal
- Scattering Correction
- Time Series Adjustment
- Sensor Fusion

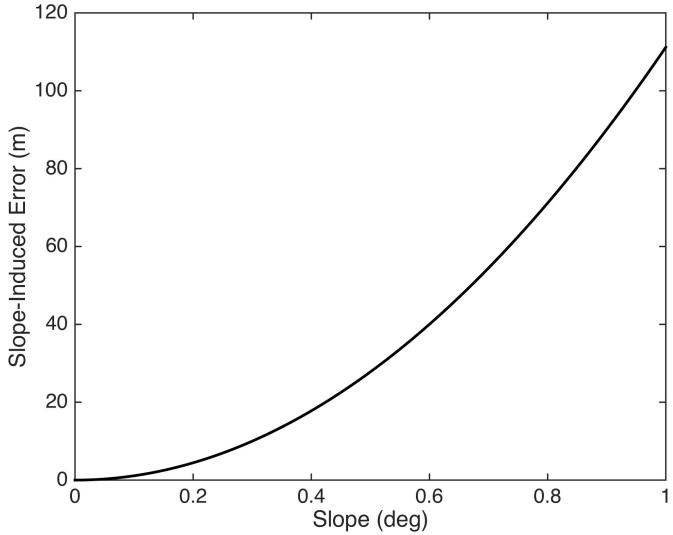
Satellite Altimetry Records:

• ERS-1	REAPER
• ERS-2	REAPER
• Envisat	L2 (GDR)
• ICESat	NSIDC R34
• CryoSat-2	

Slope Correction



α_s = surface slope



- Largest error source for radar altimeters!
- Quality of correction depends on DEM accuracy
- Laser and “SARIn” largely insensitive to surface slope!

Topography Removal

- Removal of time-invariant surface to acquire temporal changes in elevation
  - 2-D: Along and Cross-track direction
- Least-squares fitting of mathematical surface model:
  - Biquadratic (1)
  - Bilinear (2)
  - Mean (3)
- Time Series: $dH(t) = H(t) - H(t)_m + E$

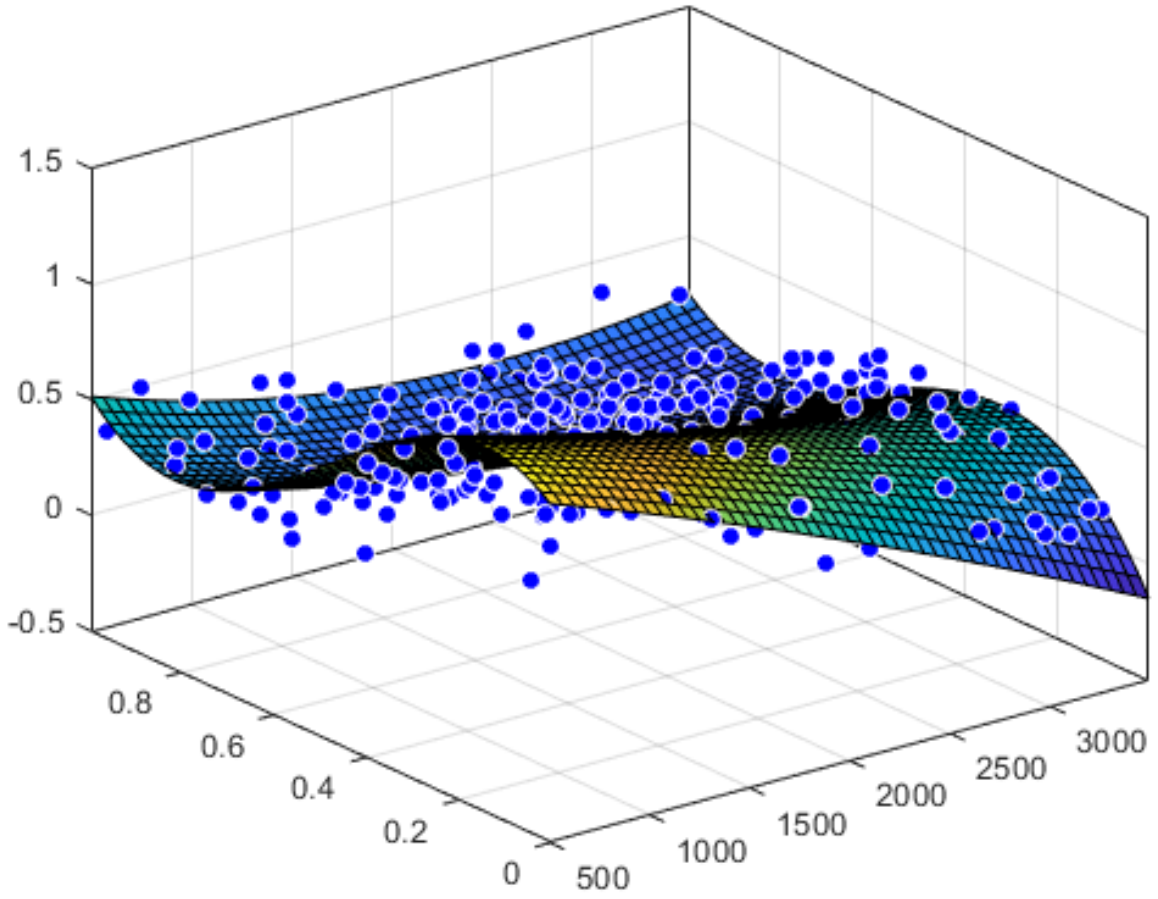


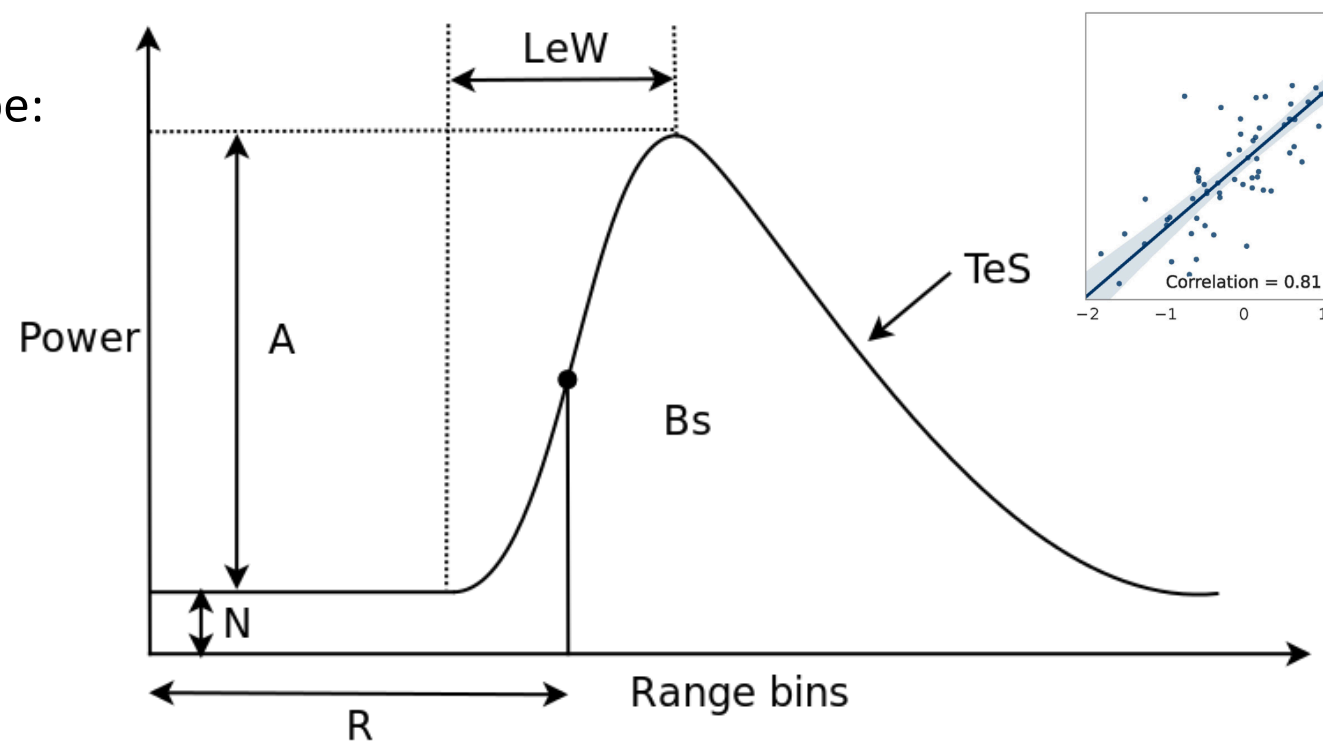
Image credit: Mathworks

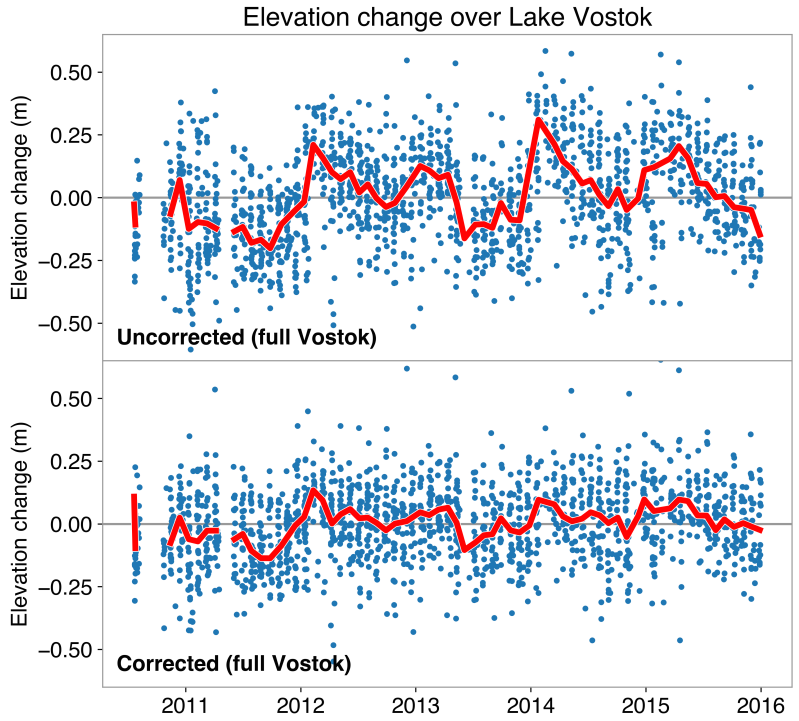
Scattering Correction – Radar (Ku-band)

Minimizing correlation between surface elevation and changes in waveform shape:

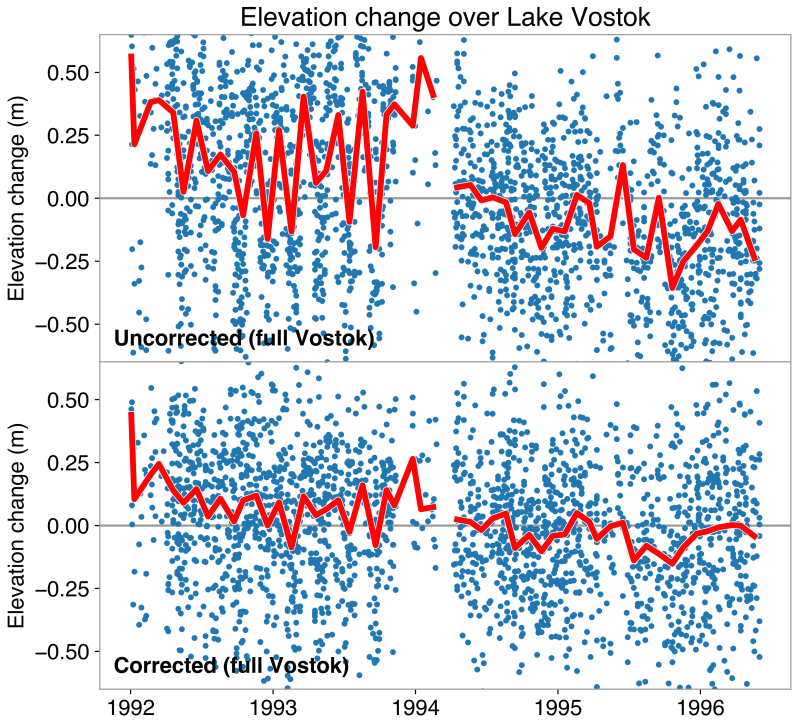
- Backscatter (**Bs**)
  - Surface regime or type
- Leading Edge Width (**LeW**)
  - Penetration
- Trailing Edge Slope (**TeS**)
  - Surface/Volume ratio

The magnitude of the correction depends on the sensitivity gradients between **dH** and **f(Bs, LeW, Tes)**

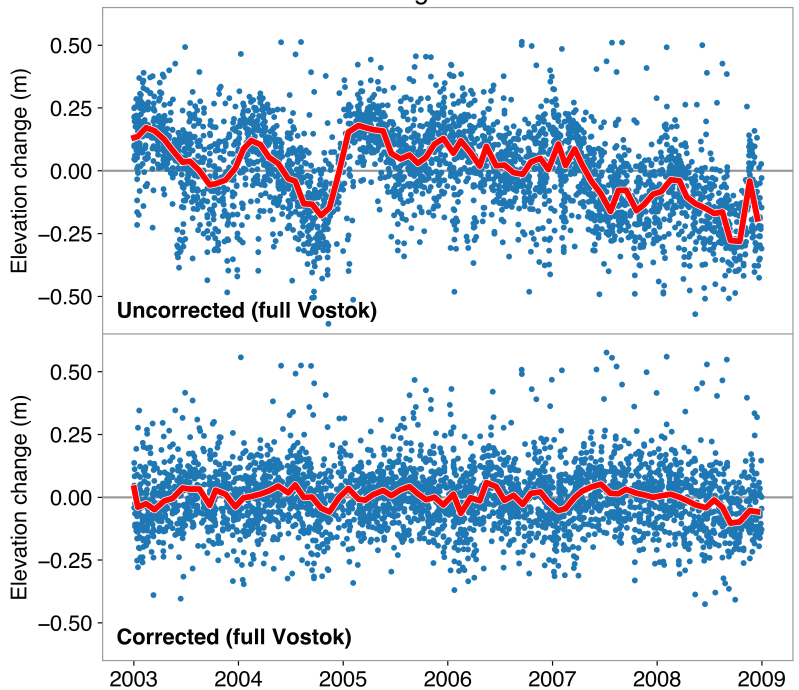




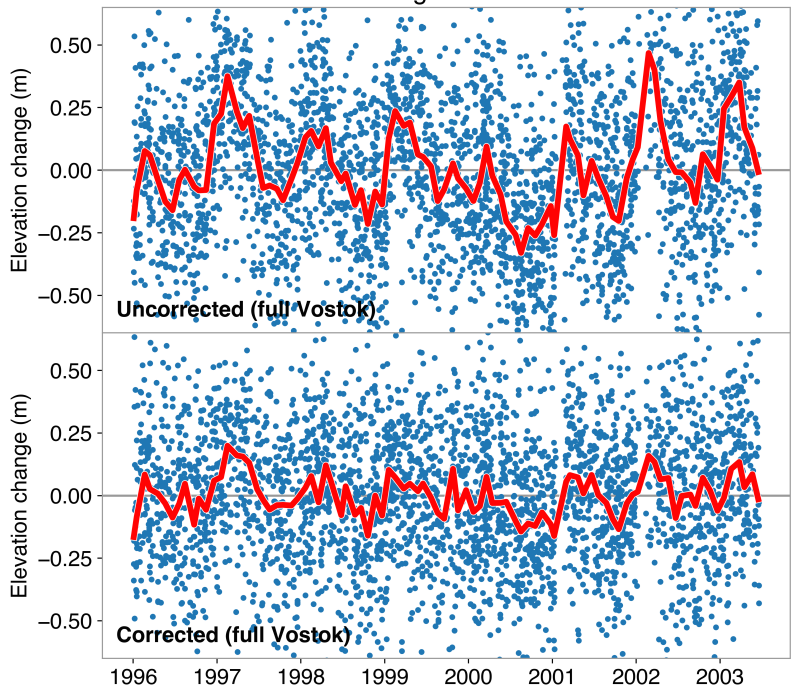
CS-2



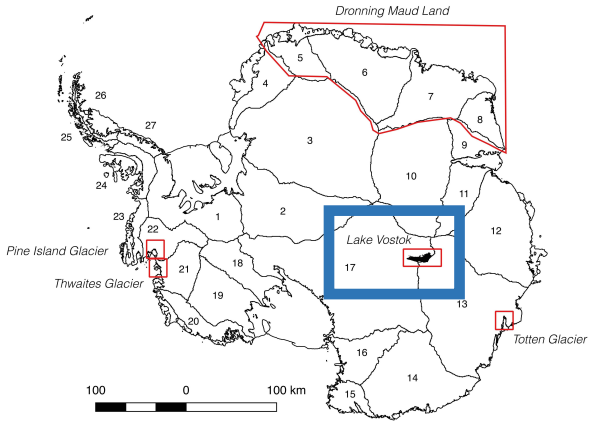
ERS-1



RA-2



ERS-2



Time Series Adjustment

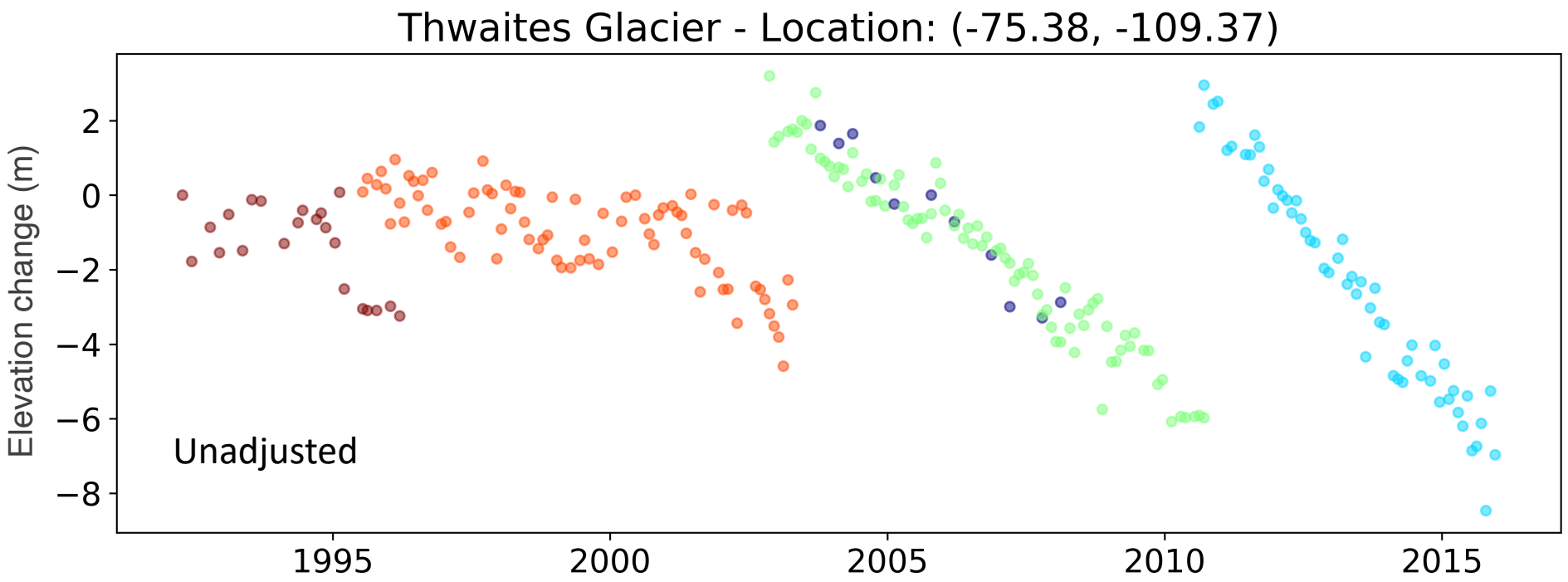
A least-squares adjustment is applied to align each sensor and to create continuous time-series:

<u>Divided into three sub-models:</u>

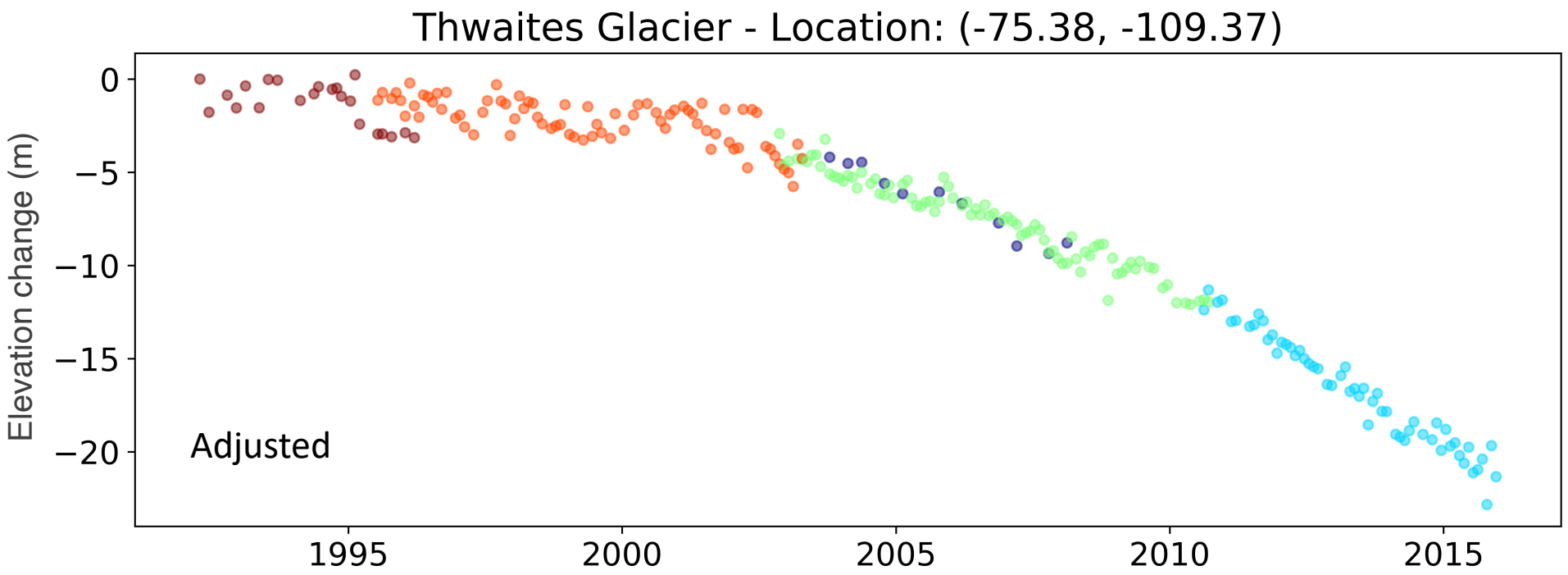
$$\mathbf{x}(t) = \mathbf{x}_{trend} + \mathbf{x}_{step} + \mathbf{x}_{cycle}$$

comprising of trend (trend), mission offsets (step) and seasonality (cycle).

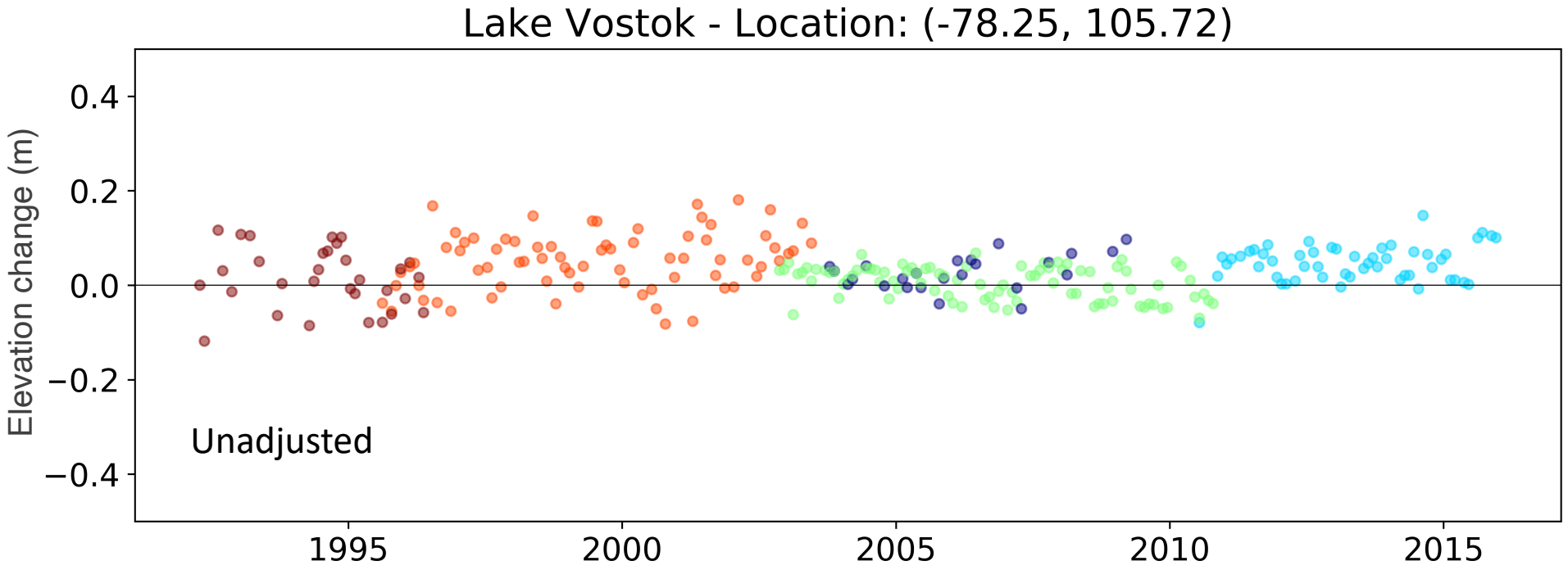
Time Series Adjustment – Single Pixel



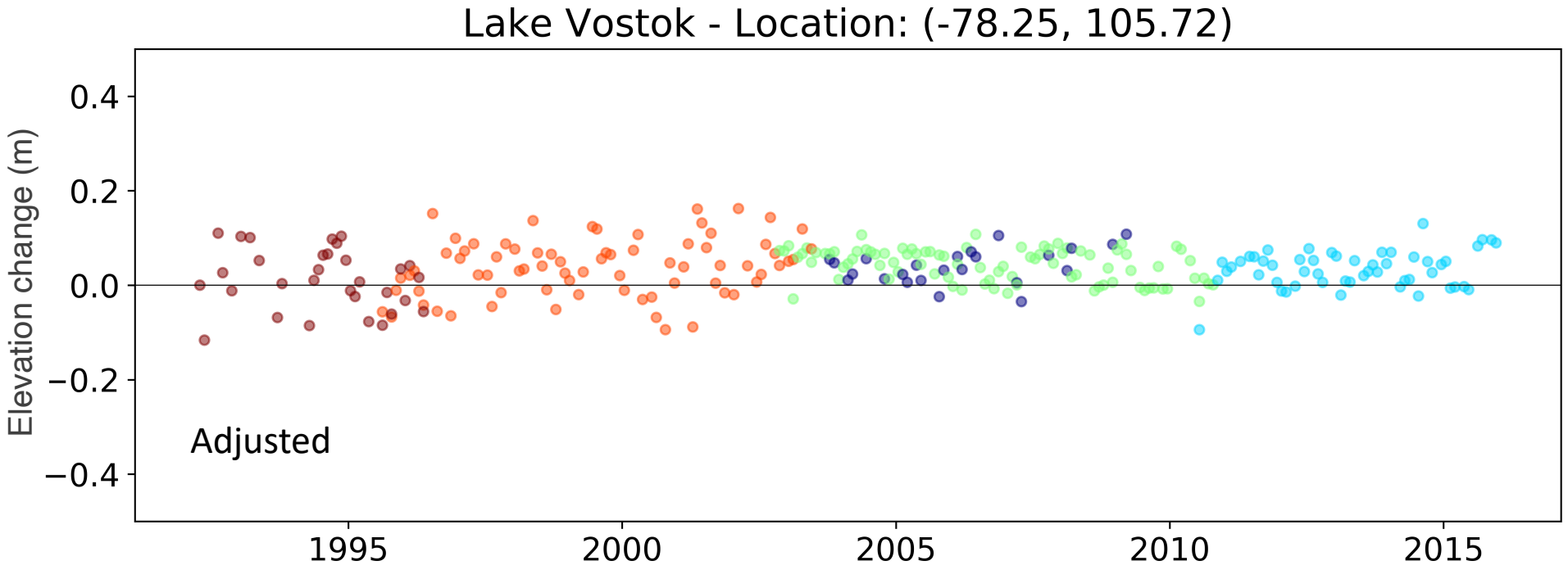
Time Series Adjustment – Single Pixel



Time Series Adjustment – Single Pixel



Time Series Adjustment – Single Pixel



Sensor Fusion - Kalman Smoother

- Kalman Filter Equations:

$$\mathbf{x}_{k+1} = \mathbf{F}_k \mathbf{x}_k + \mathbf{w}_k$$

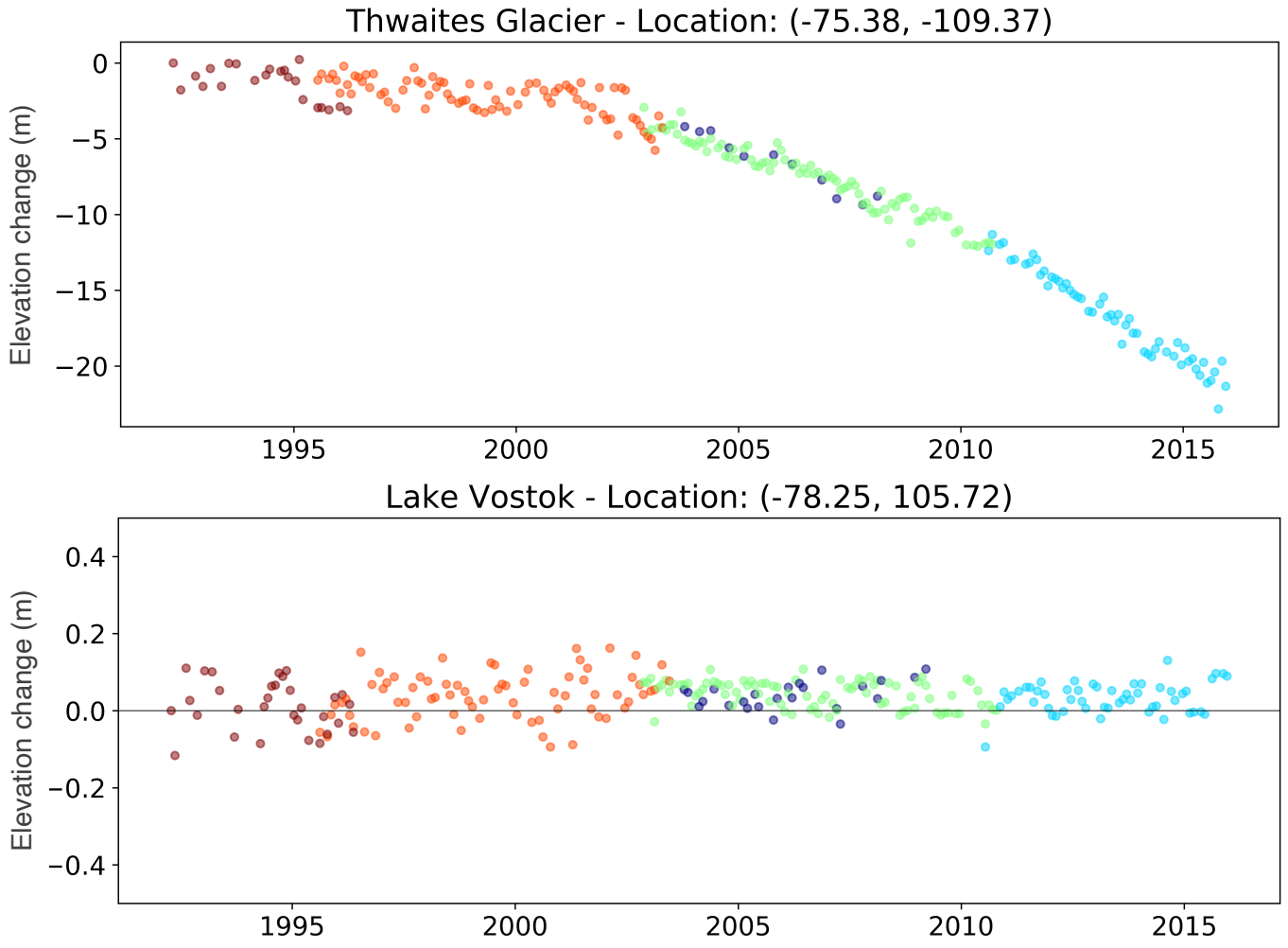
$$\mathbf{z}_{k+1} = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k$$

- State-Space Model:

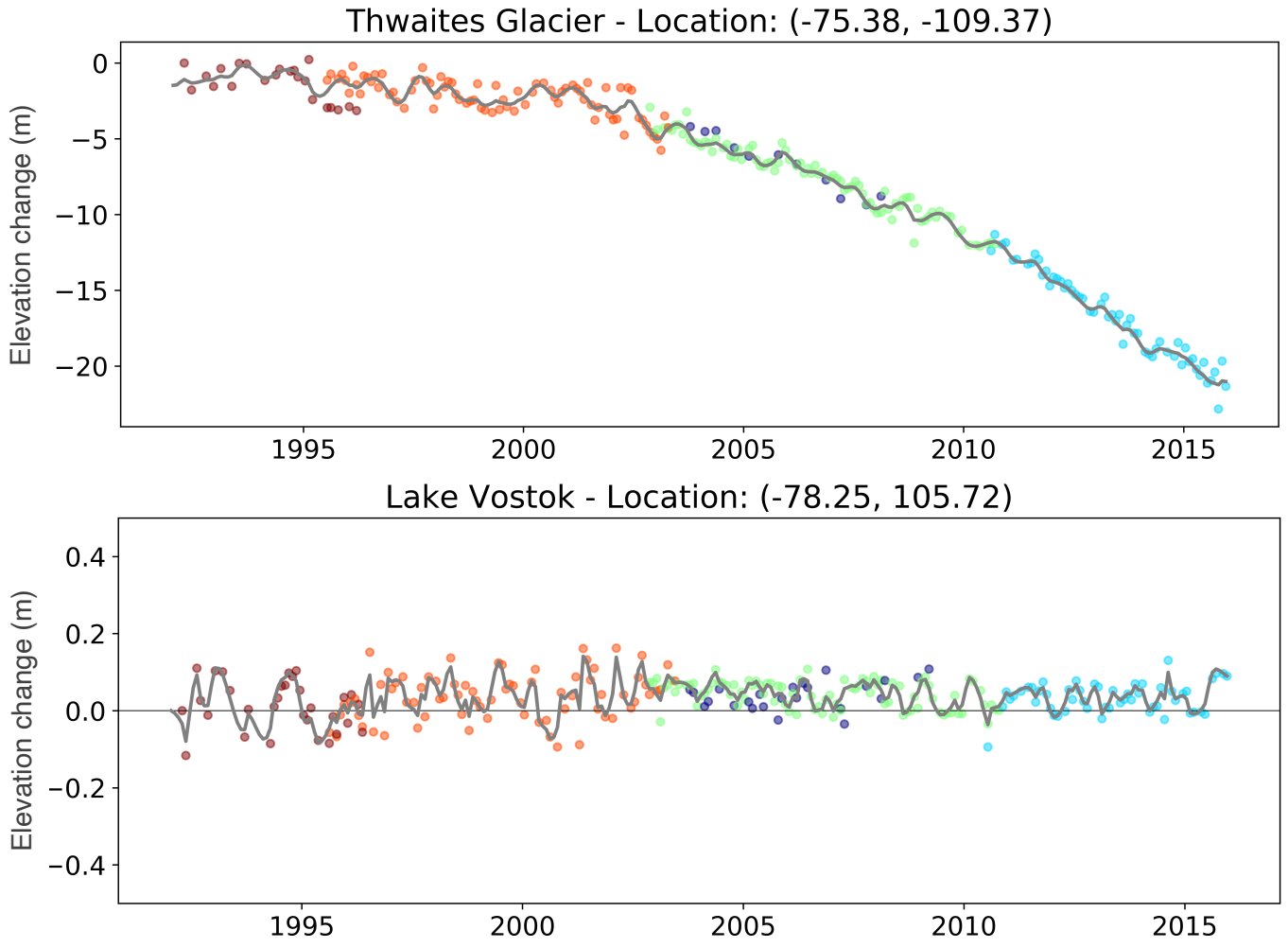
$$y(t) = y_0 + v(t)t + s(t)\sin(\omega t) + c(t)\cos(\omega t)$$

- Model as Random-Walk “(t)”

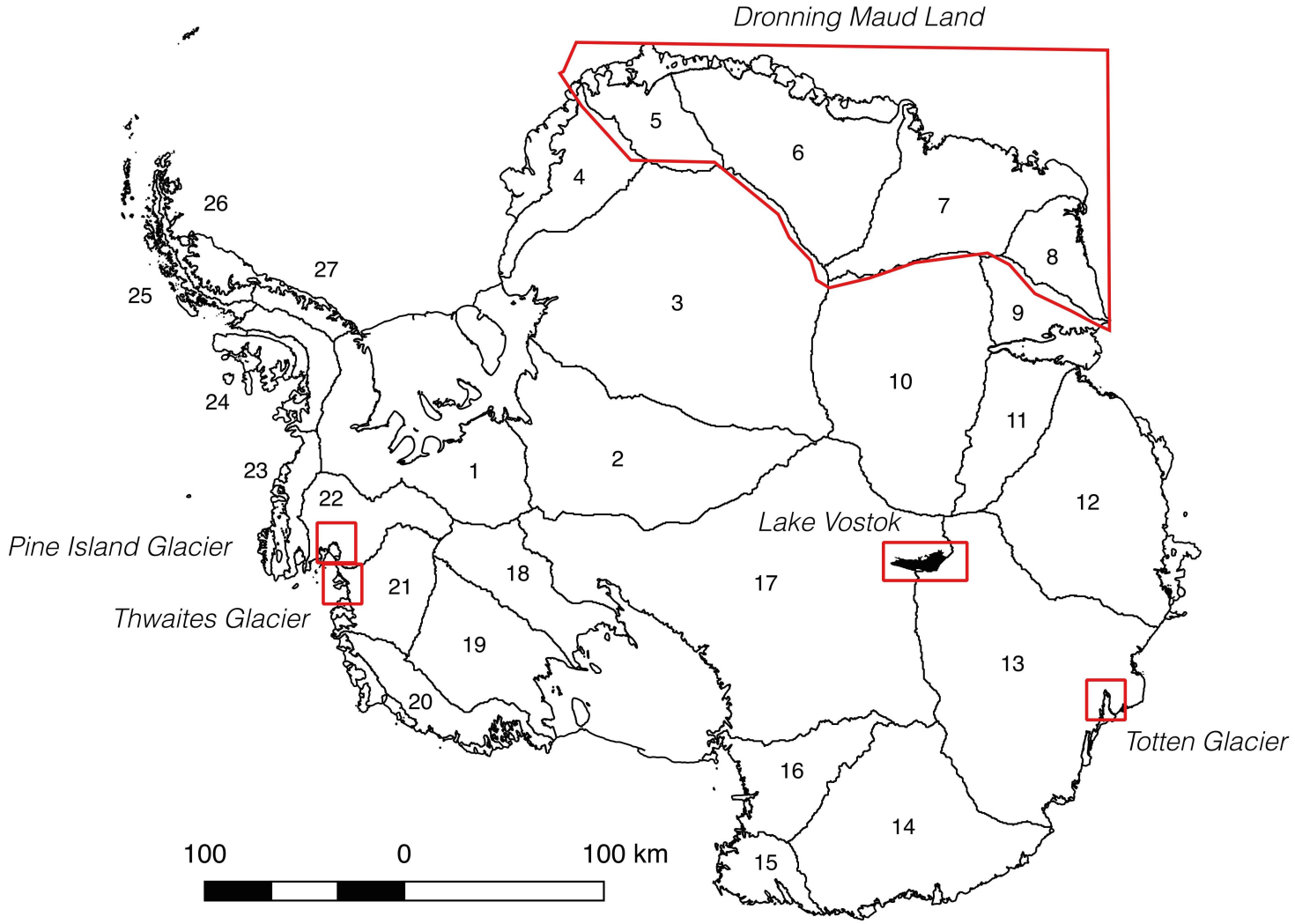
Sensor Fusion – Single Pixel



Sensor Fusion – Single Pixel

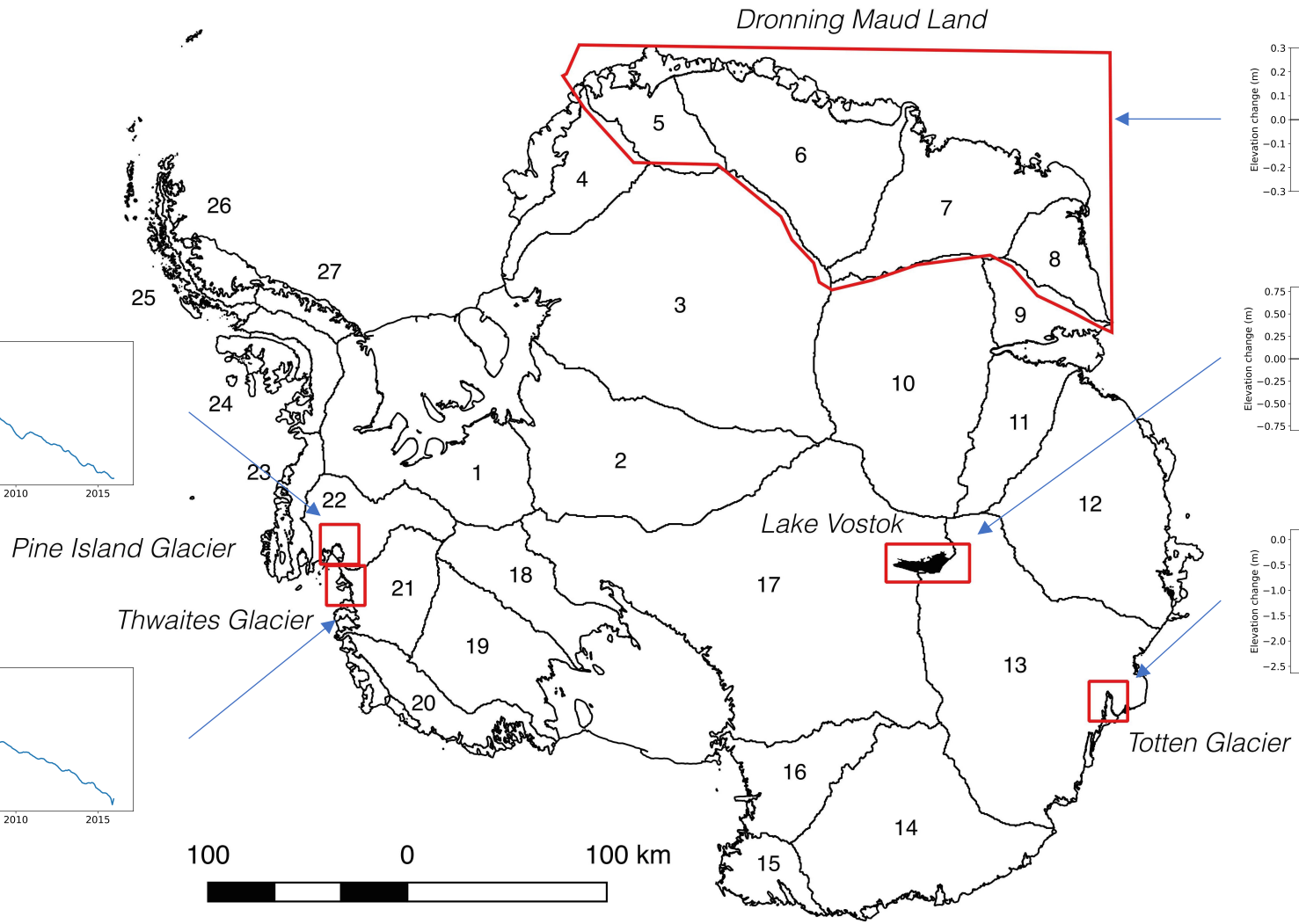


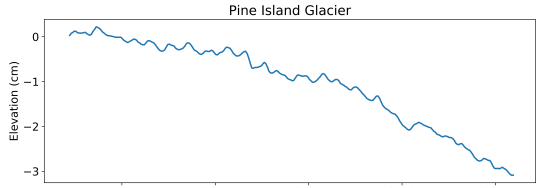
Regions of Interest

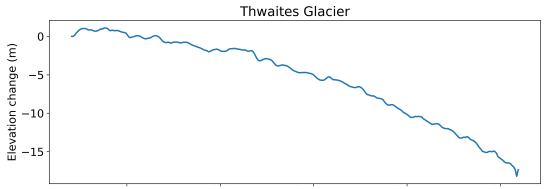


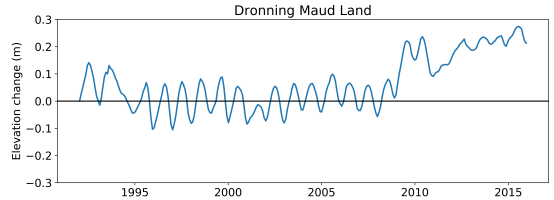
Drainage basins from *Zwally et al. 2012*

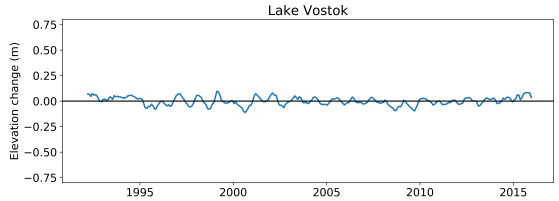
Regions of Interest

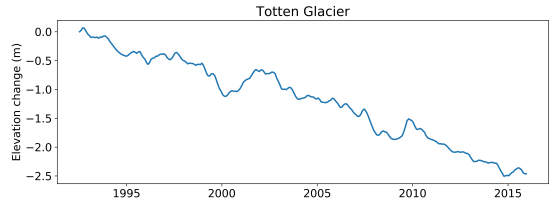






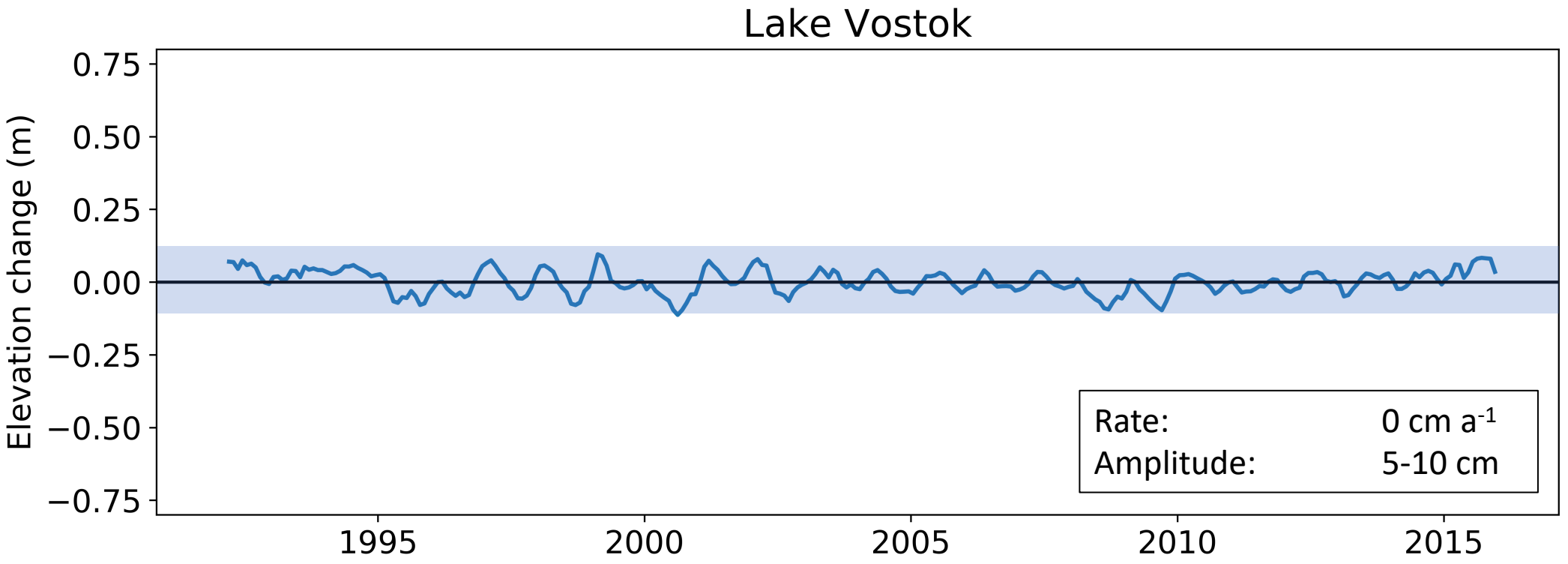




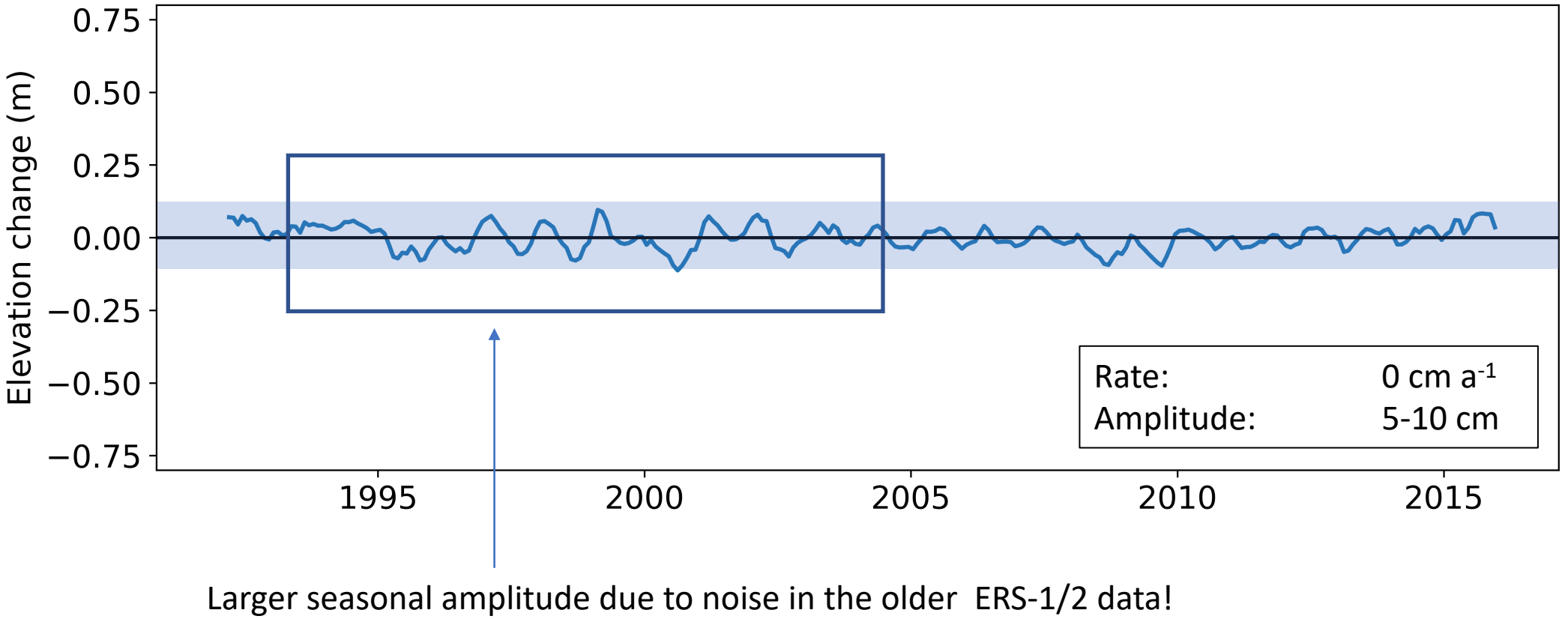


Drainage basins from *Zwally et al. 2012*

Lake Vostok

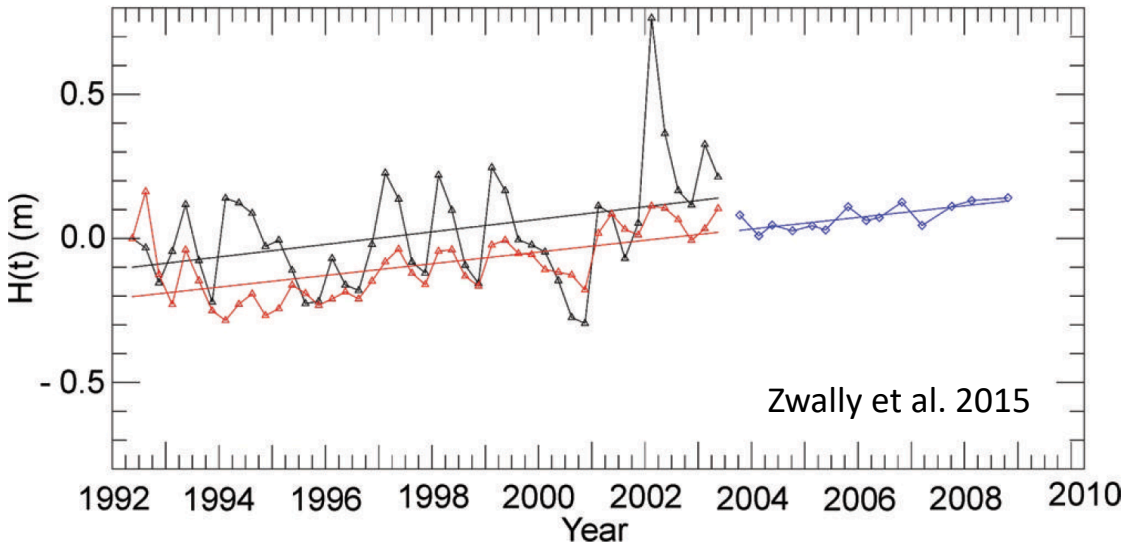

Lake Vostok
Elevation change (m)
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
1995
2000
2005
2010
2015
Rate: 0 cm a-1
Amplitude: 5-10 cm

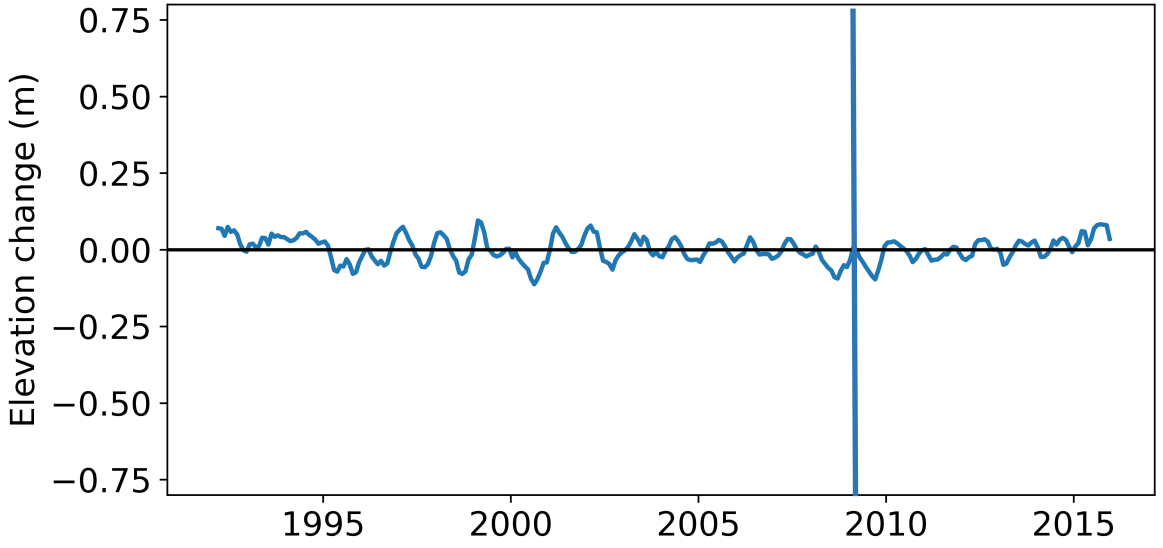
Lake Vostok



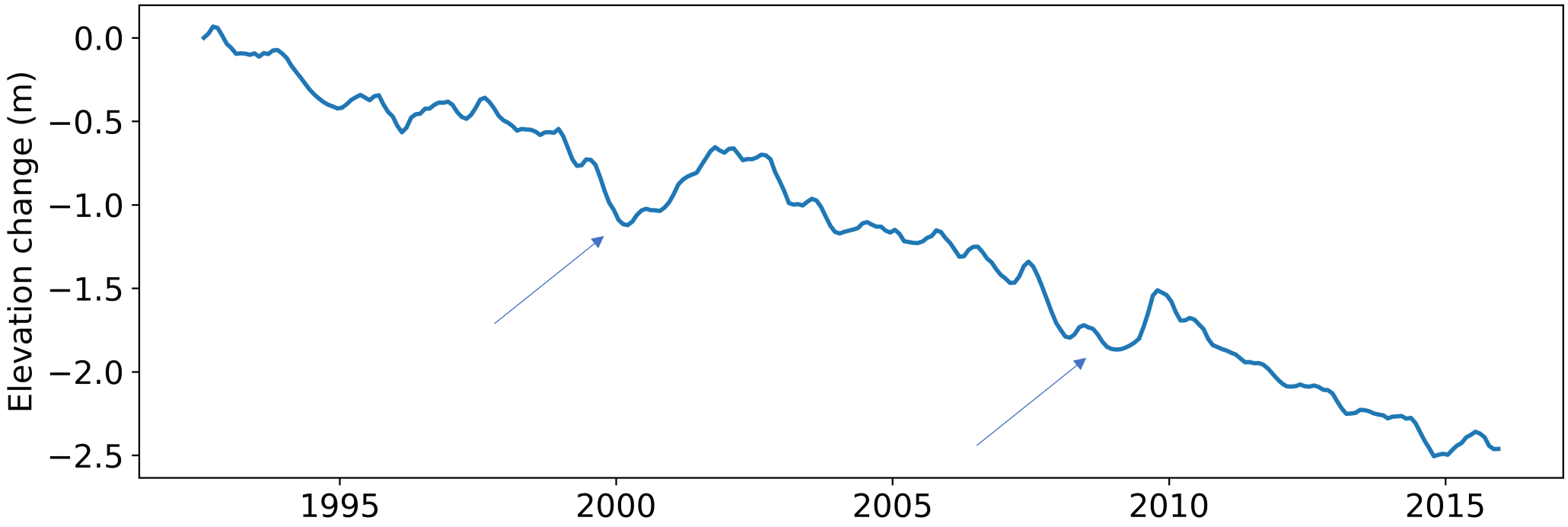
Larger seasonal amplitude due to noise in the older ERS-1/2 data!

Lake Vostok – Comparison

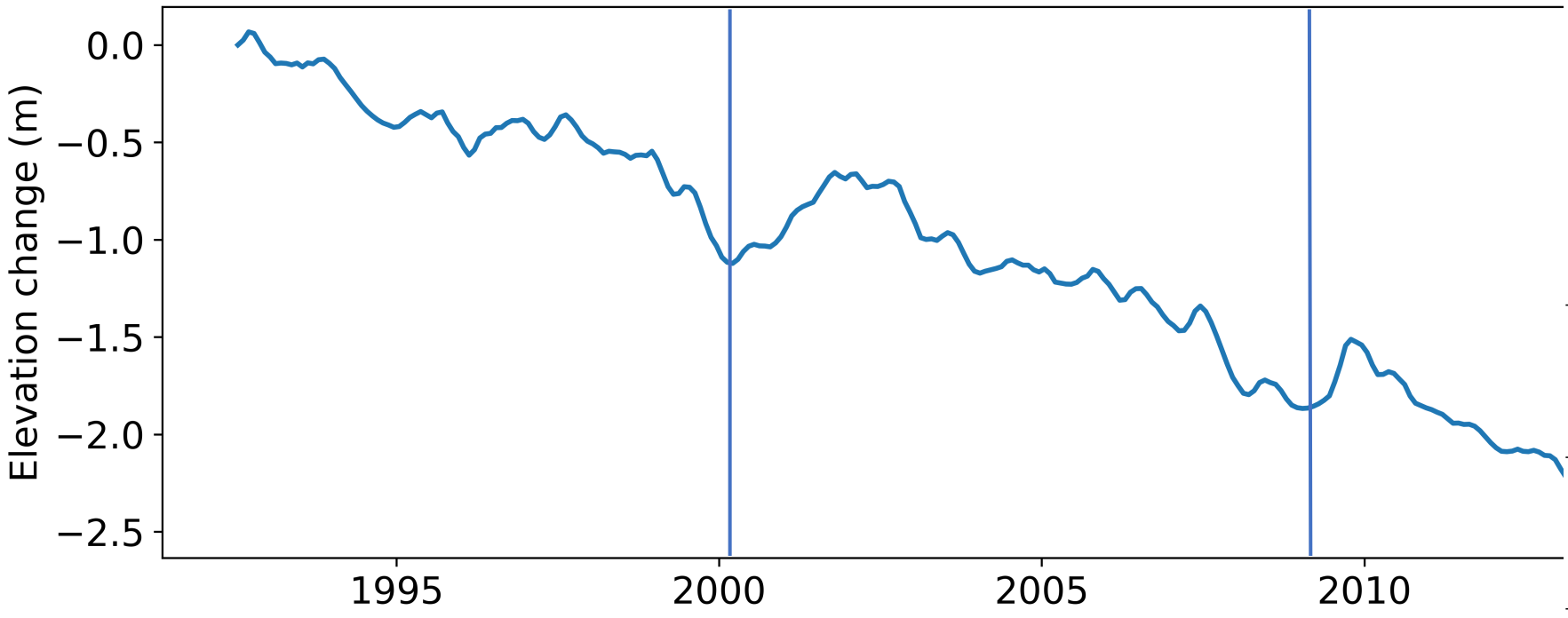


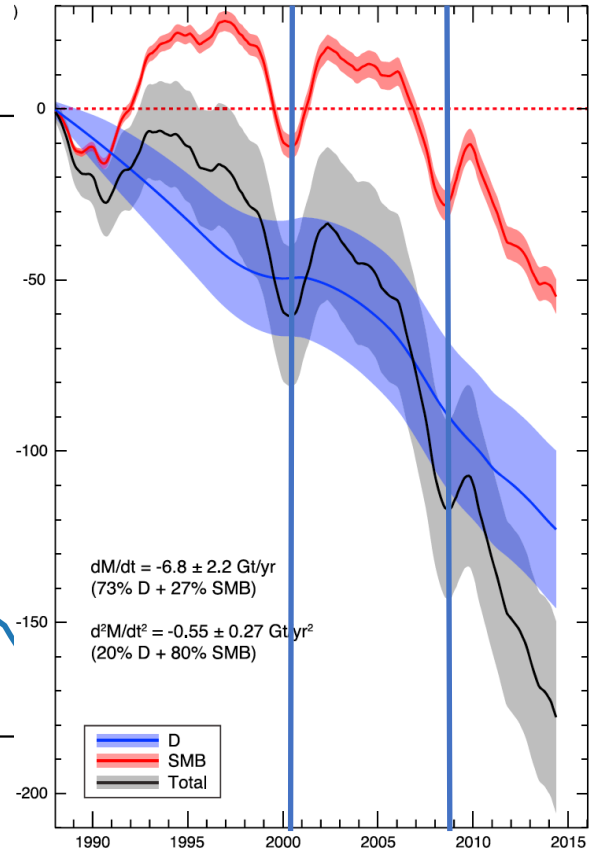


Totten Glacier



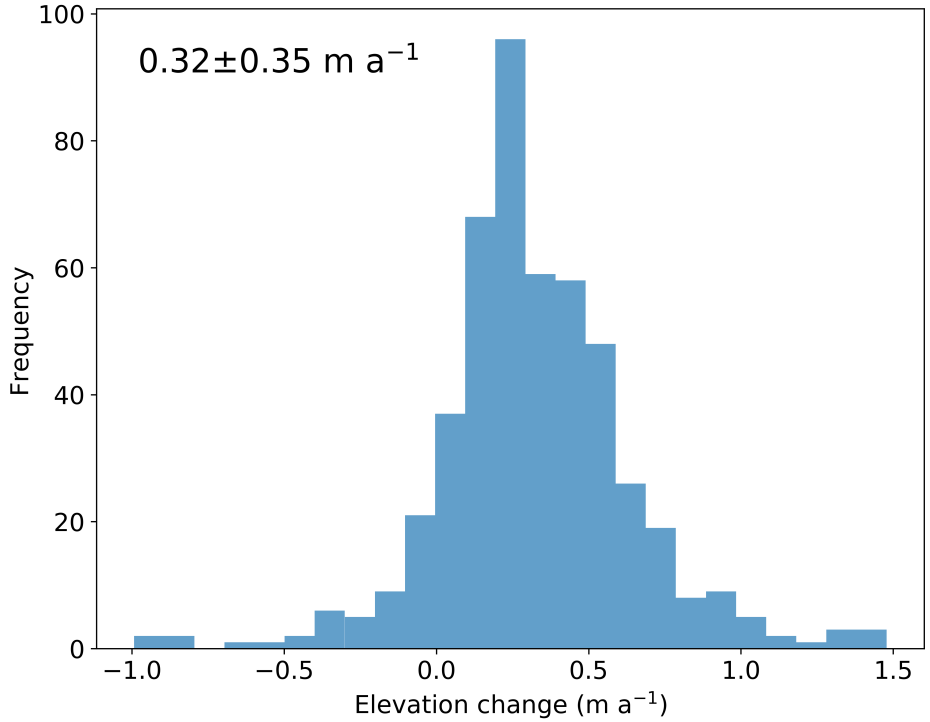
Totten Glacier



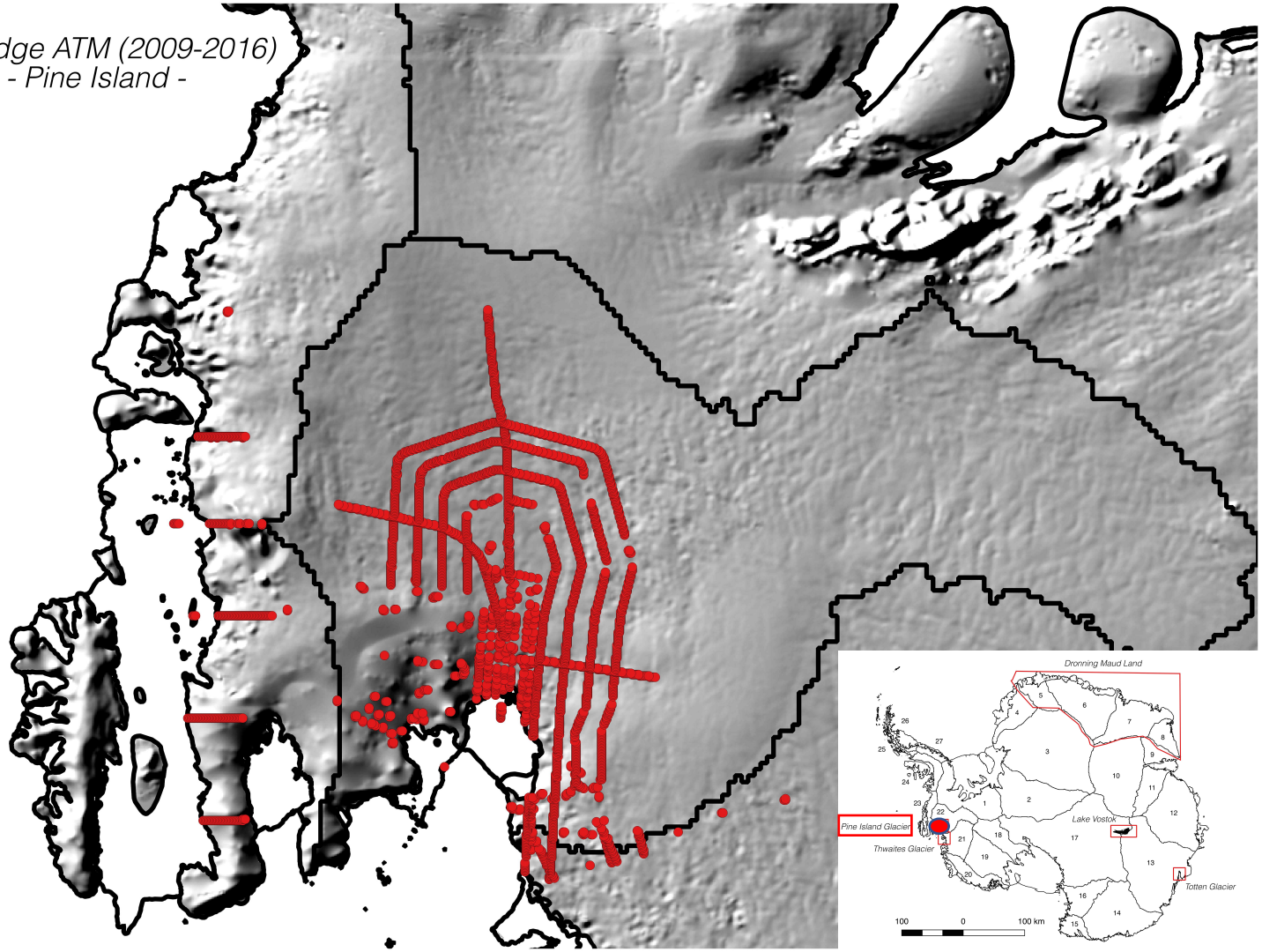


Li et al. 2016

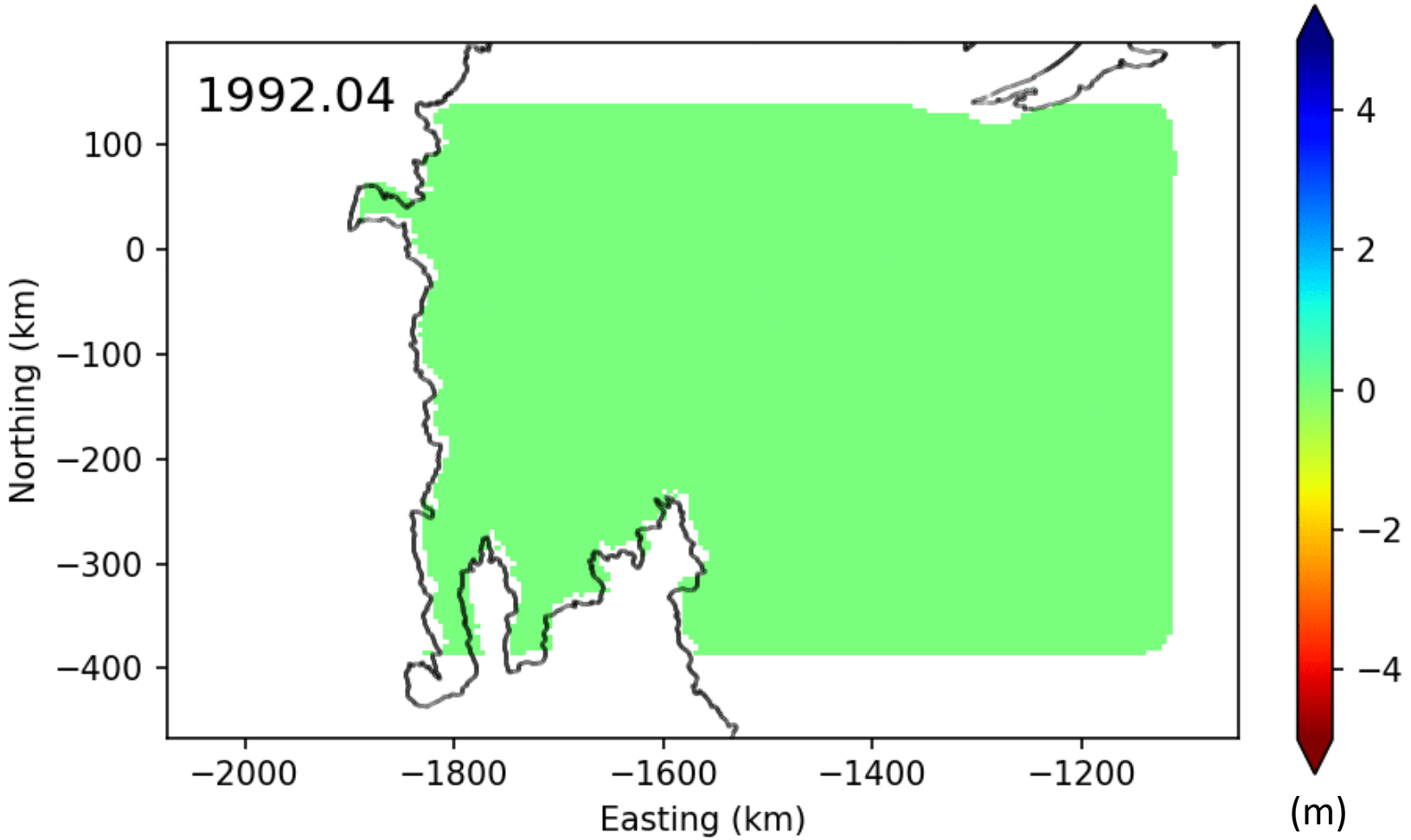
Validation to Operation IceBridge



IceBridge ATM (2009-2016)
- Pine Island -

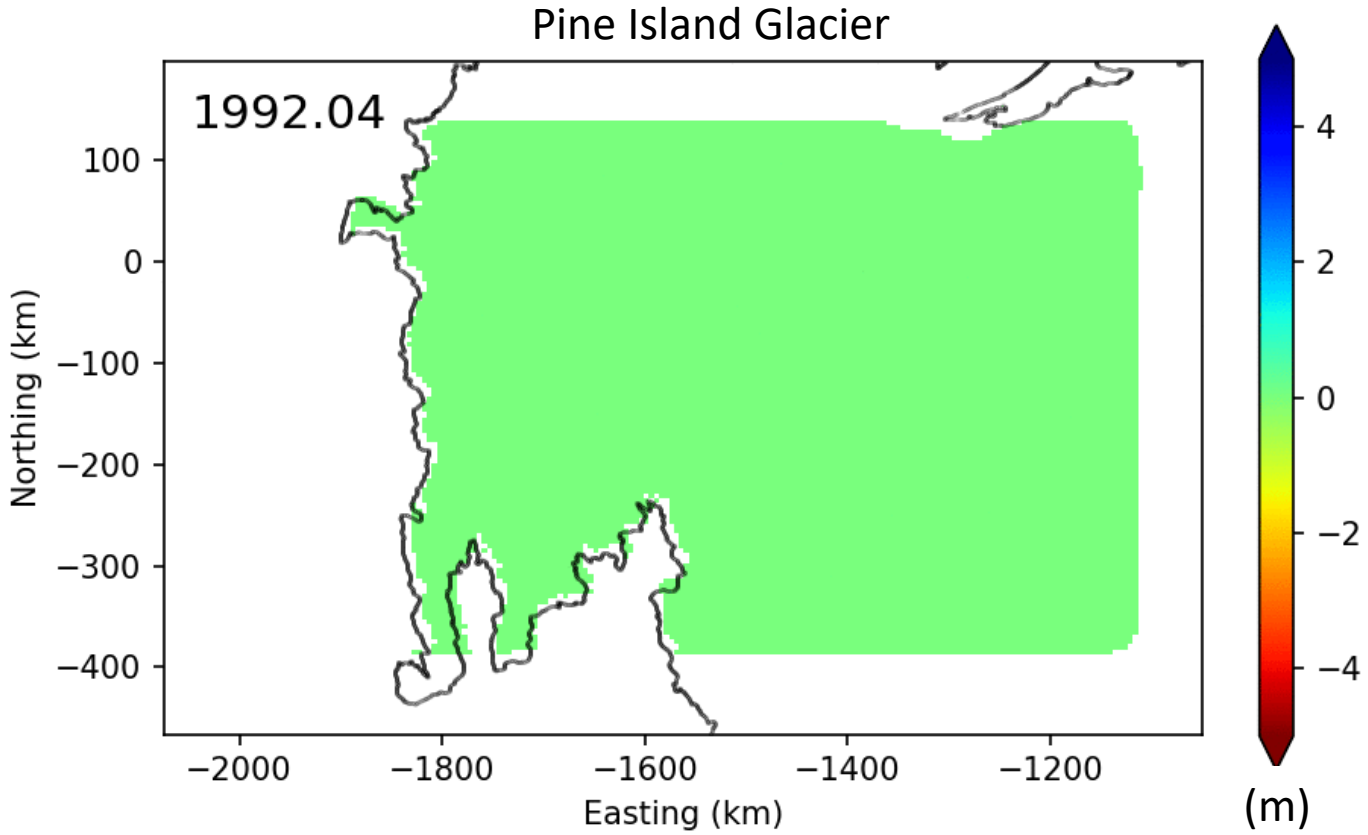


Pine Island - Temporal Evolution



Summary and Conclusions

- Procedure allows for reconstructing time series at fine spatio-temporal scales, while accounting for sensor-dependent biases and heterogeneous data quality.
- Analysis show that our applied correction minimizes the effects of surface slope, scattering regime and mission offsets.
- Initial validations show good agreement with ATM derived rates for the time period 2009-2016.
- Older missions show large noise variability (2x), which impacts the physical interpretation of the seasonal signal and possibly trend.
- Corrections applied to the altimetry observations are **non-trivial**: They affect trend, seasonality and the merging procedure
- Hence, extensive analysis is required to advance the current state-of the art methods for deriving reliable elevation trends and seasonal signals.



Thank you for listening!

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